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ESTIMATION OF THE SOIL HEAT FLUX/NET RADIATION RATIO FROM SPECTRAL DATA

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ABSTRACT

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Reliable spatial averages of surface energy balance components are difficult to obtain without an extensive hydrological measurement system. Our objective was to develop a method using remote sensing for estimating soil heat flux, one component of the surface energy balance, for a range of canopy conditions that will be applicable to regional surface energy balance studies. Net radiation (Rn) and soil heat flux (G) were measured during several days in fields of bare soil, alfalfa, and cotton at the Maricopa Agricultural Center, near Phoenix, AZ. Ground-based measurements of reflectance factors were also obtained with a multiband radiometer. Midday values of the ratio of soil heat flux and net radiation (G/Rn) were linearly related to the simple ratio and normalized difference vegetation indices. Relative to measurement errors, the estimates of G/Rn for cotton were found to be practically insensitive to changes in the value of the vegetative indices caused by spectral data collected at significantly different solar zenith and azimuth angles. Thus, multispectral data may provide a means of computing a more accurate area-averaged soil heat flux for regional energy balance studies.

INTRODUCTION

Within the last several decades there have been significant advancements in the application of remotely sensed data in the visible and infrared spectrum for evaluating the surface energy balance (cf. eq. 1). A major effort has been to employ remotely sensed data from aircraft and satellite altitudes because the information can be applied over large areas; hence it is conceivable that spatial average values of the components of the surface energy balance may be obtained without having to employ an extensive hydrometeorological ground measurement system. In computing the surface energy balance from field to regional scales an important objective has been to estimate evapotranspiration (ET). The main reason for calculating ET is that it is usually the second largest quantity in the hydrological water balance (Dyck, 1983). A number of tech-

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niques using optical remote sensing data have been developed with various degrees of complexity (Jackson et al., 1977, 1987; Soer, 1980; Price, 1982; Hatfield et al., 1983; Seguin and Itier, 1983; Gurney and Camillo, 1984; Reginato et al., 1985; Taconet et al., 1986). However, no matter how complex the model for determining ET the fundamental equation, usually approximated by four terms, is

$$Rn-G=H+LE \tag{1}$$

where Rn is the net radiation, G the soil heat flux, H the sensible heat flux and LE is the latent heat flux; all are in W m^{-2}. The sign convention of eq. 1 is G, H, and LE are positive when away from the surface and are negative when towards the surface. The sign convention for Rn is opposite to the other three components.

When eq. 1 is considered on a daily basis, the soil heat flux, G, is assumed to be negligible (e.g. Seguin and Itier, 1983). This approximation is advantageous since ground-based measurements of the soil heat flux cannot be extrapolated to large areas because it depends on soil moisture and the amount of vegetative cover. However, when extrapolating daily values of the elements in eq. 1 from remote measurements normally taken during the midday period (e.g. Jackson et al., 1977), the values of G during this period may not always be negligible. In fact even under full canopy cover situations G may be the same order of magnitude as H for well-watered conditions and may be of the same order of magnitude as LE when the vegetation is approaching sensescence. Furthermore, in early plant growth and in some cases throughout plant development, a significant portion of the soil surface is exposed to solar radiation, especially around midday. Thus, a significant amount of energy may be conducted into the soil.

To calculate the magnitude of G solely from remotely sensed data requires that it be made proportional to another term in eq. 1. A good candidate is net radiation which can be calculated with a minimal amount of meteorological information (Jackson et al., 1985). Indeed, early studies (Fuchs and Hadas, 1972; Idso et al., 1975) over bare soil suggested $G/Rn \simeq 0.3$ for practical applications. However, Idso et al. (1975) found the ratio to vary with moisture being about 0.5 for dry soils and 0.3 for wet conditions. Brutsaert (1982) argued that combining all of Idso et al.'s data together produced a coefficient of 0.4. For vegetation surfaces under full cover, Monteith (1973) suggested values for the ratio would most likely vary between 0.05 and 0.1. Monteith's conclusion was supported by a large quantity of hourly data for a short grass pasture where the daytime average was about 0.1 (DeBruin and Holtslag, 1982). For application to agriculture, this ratio must be made a function of some easily measured quantity that will allow the value of G/Rn to take on intermediate values between $\simeq 0.3$ at planting and $\simeq 0.1$ if full cover is reached. Reginato et al. (1985) obtained an empirical equation for wheat where the coefficient was calculated from the height of the crop. Choudhury et al. (1987) expressed the ratio as an exponential function of leaf area index yielding a correlation of 0.9.

For regional energy balance studies, typically very little information on crop height and phytomass is available. However, there are indications that remotely sensed vegetation indices may be a surrogate for plant phytomass, leaf area index and per cent cover (Hinzman et al., 1986; Kollenkark et al., 1982a). As a result, recent efforts have used spectral data to relate G/Rn to some vegetation index. For example, Jackson et al. (1987) employed an equation given by K.L. Clawson (unpublished) which calculates G/Rn using an exponential function of the normalized difference vegetation index. Clothier et al. (1986) showed that for alfalfa under full and sparse cover situations the simple ratio vegetation index was linearly related to midday G/Rn with $R^2 \simeq 0.76$.

Nonetheless, vegetation indices like normalized difference and simple ratio are sensitive to solar position (i.e. zenith and azimuth angles) and to the variability in soil reflectance factors. The effects of sun angle to the spectral response of vegetation canopies is dependent on the physiological properties of the vegetation such as canopy architecture and leaf angle distribution (Cowan, 1968; Kirchner et al., 1982; Kimes et al., 1985; Sellers, 1985). If it is an arable crop, row spacing, orientation and stage of growth will also affect the spectral behavior of the surface as a function of solar zenith and azimuth angles (Jackson et al., 1979; Kollenkark et al., 1982b; Kimes, 1983; Ranson et al., 1985). View angle of the sensor as well may be an important consideration (Ranson et al., 1986; Gutman, 1987; Pinter et al., 1987). The variability in soil reflectance can have a major impact on vegetation indices (Huete et al., 1985; Huete, 1987) which are normally used for modeling radiation absorption, per cent cover, biomass, and net photosynthesis of plant communities (Choudhury, 1987).

However, it is beyond the scope of the present paper to consider many of these factors affecting the value of a particular vegetation index and its relationship with G/Rn. For the present analysis it is assumed that variability in soil reflectance does not significantly affect the relationship between a vegetation index and G/Rn. Moreover it is expected that a change in the estimate of G/Rn brought about by a deviation in a vegetation index as a result of solar position effects on the measured reflectance will usually be negligible under relatively low sun zenith angles (Huete, 1987).

By considering a range of canopy cover conditions of more than one type of crop, this paper is considered an extension of the work of Clothier et al. (1986). More specifically, midday means of G/Rn are compared to multispectral vegetation indices in bare soil, alfalfa, and cotton in the hope of obtaining a generalized expression applicable to regional energy balance studies. The sensitivity of estimating G/Rn with spectral data was assessed using spectral data collected at solar zenith and azimuth angles significantly different from what was used to derive the relationship.

EXPERIMENTAL DESIGN

This investigation was part of a interdisciplinary field experiment which emphasized comparison and calibration of point measurements of energy exchange between the soil–plant–atmosphere interface with methods employing remotely sensed data to obtain a spatial distribution of latent and sensible heat fluxes.

Continuous measurements of soil heat flux, soil temperature and net radiation were recorded during June 10–13, 1988 on four agricultural fields located at the University of Arizona, Maricopa Agricultural Center in central Arizona (33.075°N latitude, 111.983°W longitude). Spectral reflectance factor data were acquired intermittently on selected days. The two cotton fields (28 and 29) and the bare soil field (32) were approximately 300 m×1500 m while the alfalfa field (21) was 250 m×750 m. These four fields provided a range of vegetative cover from bare soil to nearly full canopy cover.

Soil heat flux measurements

Bare soil

The bare soil field (32) had recently been smoothed and leveled and appeared uniform and dry. Three soil heat flux plates were buried parallel to the soil surface at a depth of 5 cm with soil temperature sensors (copper–constantan thermocouples) 2.5 cm above each plate and a fourth temperature sensor was buried at 10 cm. A single dome (polyethylene shield) net radiometer was positioned about 1.5 m above the surface. Data were recorded by an Omnidata* polycorder at 1-min intervals.

Alfalfa

The alfalfa (*Medicago sativa* L.) field (21) had been planted in 1984 and periodically harvested for hay. The vegetative cover was not homogeneous, rather the field contained patches (randomly situated) of thatch from previous harvests covering the soil surface. Plant cover was estimated to be around 75%. Two weeks prior to this experiment the alfalfa had been cut at 10 cm, and it had been flood irrigated 1–2 days prior to this experiment. The soil was saturated during instrument setup on DOY 160. Plant height increased from 0.43 to 0.52 m during the experimental period. The heat flow plates and temperature sensors were buried judiciously to account for the partial canopy situation. One sensor was placed in a thatch-covered area, another underneath the canopy while the third was placed in between the two; this was assumed to represent a partial canopy setting. A fourth thermocouple at a depth of 10 cm was

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placed under partial canopy. The net radiometer (facing south) was positioned over an area representing average surface conditions (i.e. viewing both bare soil and vegetation) approximately 1.5 m above the top of the canopy. Data were recorded by an Omnidata polycorder at 1 min intervals.

Cotton Field 28

Cotton (*Gossypium hirsutum* L. Delta Pine 77) in Field 28 was planted on March 29, 1988. The west half of the field was replanted on April 14 because of poor emergence of the first planting. Row direction was north–south. Rows were spaced 1.0 m apart with 0.17-m-deep furrows between each row. At the time of the experiment, cotton in the east half of the field was 0.29 ± 0.04 m high compared to 0.19 ± 0.03 m high in the west half of the field. Plant density and ground cover were 11.8 plants m^{-2} and 20% in the eastern half compared to 7.6 plants m^{-2}, and 11% in the western half of the field. The plants were distributed in clumps along the furrow beds. Gaps of bare soil along the furrow beds also existed on the east side, albeit they were smaller in size and fewer in number. Furthermore, the practice of flood irrigating a group of furrows at a time resulted in a gradual increase in surface soil moisture (i.e. 0–5 cm) from the east to the west end of the cotton field.

To consider the possibility of an observable difference in the soil heat flux due to vegetative cover, a site was chosen which would allow measurements over both the more (east site) and less (west site) developed cotton plants. The macrotopographic relief of the cotton bed and furrows was determined by sampling furrow depth every 0.10 m along a meter stick traversing one wavelength of the furrow (Table 1).

Five thermocouples were buried (2.5 cm) traversing the furrow with a sixth buried at 10 cm from the bottom of the furrow. Seven heat flow plates were buried (5 cm) traversing the furrow and parallel to the surface. Figure 1 is a schematic illustrating placement of the sensors. A net radiometer (double dome polyethylene shielded instrument) for each site was positioned on the bed about 1.5 m above the crop facing south. Data were recorded every 4 s by a Campbell Scientific 21X datalogger connected to a multiplexer unit. Both the datalogger

TABLE 1

Furrow profiles in cotton fields. Data are means of five random transects in each field

Field	Distance between rows (m)										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	Depth from bed, mm										
Cotton 28	0	0	−25	−73	−125	−167	−138	−85	−31	0	0
Cotton 29	0	0	−34	−94	−133	−164	−135	−82	−34	0	0

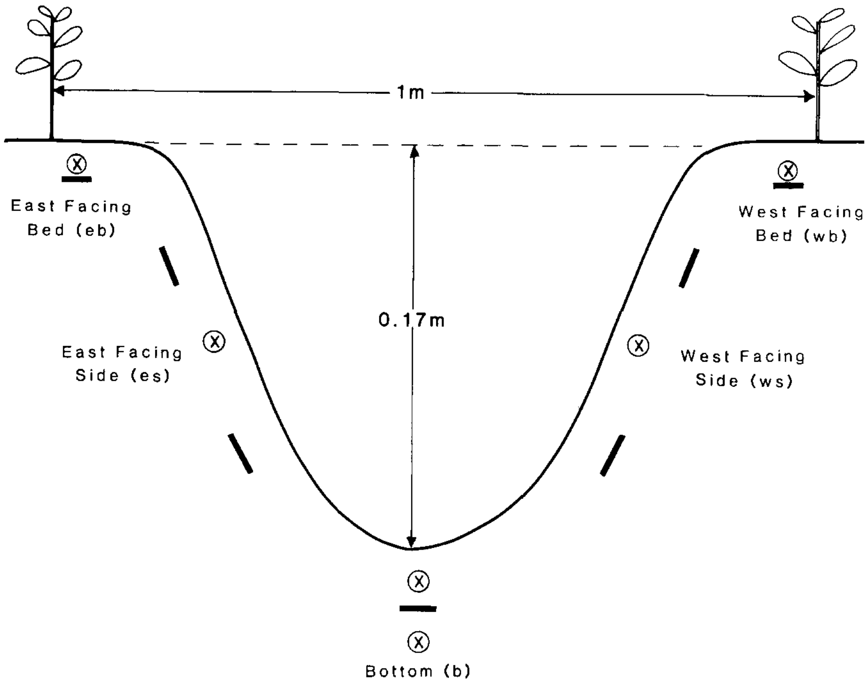

Fig. 1. A schematic drawing illustrating positions of the flux plates (–) and thermocouples (×) in Field 28. The positions are labeled relative to furrow and topographic orientation.

and multiplexer were stored in the same styrofoam container to minimize temperature gradients between them. Six-minute averages were stored and later used to compute the half-hourly values.

Cotton Field 29

Cotton in Field 29 was planted on March 31, 1988 with similar furrow orientation and dimensions as Field 28 (Table 1). The cotton was significantly larger (0.36 ± 0.04 m high) and more vigorous than in Field 28 at the time of the experiment. The cover was around 30%.

Installation of the sensors on DOY 161 in the upper 5 cm of soil was difficult because the soil was hard and dry and the surface was very cloddy. The field had not been irrigated since the last field cultivation. Five soil heat flux plates and five thermocouples were positioned along the furrow with one additional temperature sensor at 10 cm below the bottom of the furrow. Two net radiometers, a single and a double dome, were positioned on top of the beds about 1.5 m above the surface pointing south. Sensor placement in the furrow was similar to Cotton Field 28. Data were recorded every 2 s by a Campbell Scientific 21X datalogger with 6-min averages stored and later used to compute 0.5-h means.

Data on soil moisture and characteristics

Gravimetric samples for estimating soil moisture were collected for most of the sites, but not for every day of the experiment. Bulk density measurements for Fields 28 (east and west sites), 21, and 32 were performed on DOY 165. Tables 2 and 3 summarize the soil moisture/bulk density data collected and estimated for the missing days. The volumetric fractions of mineral soil and organic matter were estimated for the fields using a detailed soils map of Maricopa Farm (Post et al., 1989). This information was used to estimate the soil volumetric heat capacity.

Multispectral reflectance data

Spectral radiances were measured with a multiband radiometer (Barnes 12-1000) with filters simulating the bands of the Landsat Thematic Mapper. The radiometer was attached to the end of a short boom mounted on a back pack-type frame which positioned the radiometer approximately 1.7 m above the soil. With a 15° field of view, the radiometer viewed a 0.4-m-diameter area of the soil. In order to adequately represent the mean reflectance factor of the

TABLE 2

Gravimetric soil moisture in bare soil, alfalfa, and cotton fields ($g\ g^{-1}$)

Field	DOY	Location		
		Bed	Side	Bottom
Bare soil	162	0.04	NA	NA
	163	0.04	NA	NA
	164	0.04	NA	NA
	165	0.04	NA	NA
Alfalfa	162	0.17	NA	NA
	163	0.15	NA	NA
	164	0.14	NA	NA
	165	0.13	NA	NA
Cotton 28E	163	0.14	0.13	0.13
	164	0.14	0.13	0.13
	165	0.14	0.12	0.12
Cotton 28W	163	0.16	0.13	0.14
	164	0.15	0.11	0.12
	165	0.14	0.10	0.10
Cotton 29	163	0.10	0.10	0.10
	164	0.35	0.35	0.35
	165	0.35	0.35	0.35

NA = not applicable.

TABLE 3

Bulk density of soils in bare soil, alfalfa, and cotton fields (g cm^{-3})

Field	Location		
	Bed	Side	Bottom
Bare soil	1.44	NA	NA
Alfalfa	1.60	NA	NA
Cotton 28E	1.25	1.23	1.38
Cotton 28W	1.39	1.33	1.33
Cotton 29	1.32	1.32	1.32

NA = not applicable.

TABLE 4

Acquisition dates and times for vegetation indices calculated from reflectance factor data using Barnes 12-1000 multiband radiometer. Estimates of midday (1030–1430 h MST) values of GS/Rn are listed

Field	DOY	Time (h MST)	Solar angle (°)		NIR/Red	NDVI	$\overline{GS/Rn}$	$\overline{GS/Rn}$[a] Corrected
			Zenith	Azimuth				
Alfalfa	162	1239–1242	11	201	5.45	0.64	0.19	0.21
	163	1009–1014	31	101	8.65	0.79	0.175	0.20
	165	1215–1220	11	164	9.51	0.80	0.14	0.16
Bare soil	162	1300–1303	13	216	1.20	0.09	0.32	0.32
	165	1426–1429	28	257	1.21	0.09	0.29	0.29
Cotton 28E	162	1330–1338	17	237	1.82[b]	0.29[b]	0.26[c]	-
	163	0905–0913	45	90	2.30	0.39	0.28	0.33
	165	0906–0913	45	90	2.39	0.41	0.27	0.33
Cotton 28W	162	1330–1338	17	237	1.40[b]	0.17[b]	0.27[c]	-
	163	0905–0913	45	90	1.86	0.30	0.25	0.30
	165	0906–0913	45	90	1.84	0.30	0.24	0.30
Cotton 29	162	1344–1348	19	244	2.27[b]	0.38[b]	0.26[c]	-
	163	0919–0923	42	92	3.20	0.52	0.19	0.19
	165	0918–0922	42	92	4.06	0.60	0.20	0.23

[a]$\overline{GS/Rn}$ corrected for differences in diffusivities between soil, transducer and calibrating medium.
[b]Values of NIR/Red and NDVI not used in deriving equations shown in Fig. 5.
[c]GS/Rn computed with NIR/Red values and the expression in Fig. 5.

cotton planted in rows spaced 1.0 m apart, eight observations were acquired at equal intervals along a 2.0-m transect perpendicular to the row direction. In the alfalfa and bare soil fields, eight observations were acquired as the operator walked along a 10-m transect. At least four transects near the soil heat flux sites in each field were sampled. Dates and time of acquisition of the ground-based reflectance factor data are presented in Table 4. Also listed in Table 4 is the average of the simple ratio and normalized difference vegetation index (see below) for the transects in each field. All data were acquired under clear skies.

Spectral radiances of a painted $BaSO_4$ reference panel were also measured before the first transect and after the last transect of each field. Reflectance factors were calculated as ratio of scene response to reference panel response after correcting for illumination angles and the non-ideal properties of the reference panel.

The reflectance factor data were analyzed as vegetation indices. The NIR/Red or simple ratio is the ratio of reflectance factors in the near-infrared (760–900 nm) and red (630–690 nm) bands. The normalized difference vegetation index (NDVI) is the difference between the NIR and Red reflectance factors divided by their sum.

METHOD FOR CALCULATING SOIL HEAT FLUX

The soil heat flux at the surface was estimated by a combination of soil calorimetry and measurement of the heat flux density at a depth of 5 cm (0.05 m) using the heat flow plates (Fuchs and Tanner, 1966). Hence the change in heat storage of the soil layer above the plate is added to the plate values

$$GS=G_{0.05}+\int_{0}^{0.05} C(z)\ (\partial T_s(z)/\partial t)\ \mathrm{d}z \tag{2}$$

where $C(z)$ is the volumetric heat capacity (J m^{-3} K^{-1}), T_s the soil temperature (°C), t time (s), z the depth (m) and $G_{0.05}$ is the heat flux density (W m^{-2}) measured at 0.05 m below the soil surface. In this study the volumetric heat capacity was assumed constant for the storage layer (0–5 cm) and a mean temperature for the layer was measured at a depth of 2.5 cm. An equation from DeVries (1963) was employed to determine the volumetric heat capacity (C_s)

$$C_s=(1.94\theta_m+2.5\theta_c+4.19\theta)\times 10^6 \tag{3}$$

where θ_m, θ_c and θ are the volume fractions of mineral soil, organic matter and water, respectively. With the above approximations for C_s and T_s, the integral in eq. 2 was evaluated using half-hourly values of soil temperature and daily estimates of soil moisture. The equation for the change in storage had a finite difference form

$$S=27.8(1.94\theta_m+2.50\theta_c+4.19\theta)\ (\bar{T}_{s(i)}-\bar{T}_{s(i-1)}) \tag{4}$$

where S is the storage term (W m^{-2}), T_s the half-hourly value of soil temperature and the subscript i represents the half-hourly time step. Table 5 lists eq. 3 simplified by having estimated values of θ_m and θ_c for each field inserted into the expression.

TABLE 5

A list of DeVries (1963) equations used for each field to estimate volumetric heat capacity (J m^{-3} K^{-1}). The equation is reduced to a function of only gravimetric soil moisture (*GSM*), because estimates of the volume fraction of mineral soil, θ_m, and organic matter, θ_c, are inserted into eq. 2

Field	Volume fraction		Volumetric heat capacity
	θ_m	θ_c	
Bare soil	0.52	0.02	$C_s = (1.06 + 6.03GSM) \times 10^6$
Alfalfa	0.58	0.02	$C_s = (1.17 + 6.69GSM) \times 10^6$
Cotton 28[a]	0.48	0.02	$C_s = (0.982 + 5.53GSM) \times 10^6$
Cotton 29[b]	0.48	0.02	$C_s = (0.982 + 5.53GSM) \times 10^6$

[a] A mean bulk density was used for Field 28 but C_s was determined for the bed, bottom and side of the furrow for each site from the *GSM* values given in Table 2.
[b] It was assumed *GSM* was constant from the bed to the bottom of the furrow in Field 29 before and after irrigation (see Table 2).

In some cases differences between the diffusivity of the soil, heat flow transducers, and medium used to calibrate the plates may be significant enough to warrant a correction to the plate values (Philip, 1961; Fritschen and Gay, 1979). This essentially involves adjusting the plate calibration (e.g. Weaver and Campbell, 1985). However, estimation of the soil diffusivity with the soils information available with the present data set may give misleading results (see, e.g. DeVries and Philip, 1986, appendix). Therefore, the analysis of $\overline{GS}/Rn$ and vegetation index with both corrected and uncorrected values of the soil heat flux was performed. Corrections were obtained with a procedure outlined in DeVries (1963) (see also Kimball et al., 1976) for calculating soil diffusivities and an expression from Philip (1961) for adjusting the calibration factor of the flux plate. In what follows, the values of soil heat flux and the ratio of soil heat flux to net radiation will pertain to the uncorrected values unless otherwise specified.

RESULTS AND DISCUSSION

Estimates of the soil heat flux

In the bare soil field the mean soil heat flux at the surface, $\overline{GS}$, was calculated by averaging the three soil heat flow plates and corresponding storage terms. The soil heat flux increased rapidly as *Rn* became positive and reached a maximum about 1.5 h before solar noon, i.e. 1230 h MST (see Fig. 2). The difference between time of maximum *Rn* and maximum *GS* is a result of the lag time between maximum temperature and solar noon (Monteith, 1973).

In the alfalfa, the effects of shading on the diurnal patterns of soil temper-

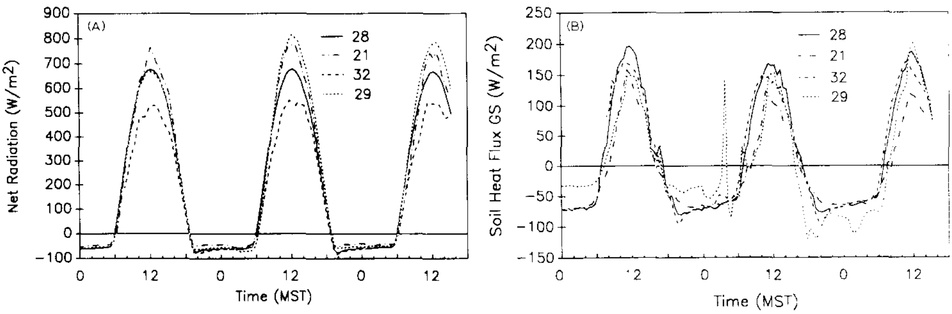

Fig. 2. Values of Rn (a) and $\overline{GS}$ (b) for DOY 163-165 in bare soil Field 32, and alfalfa Field 21, cotton Field 28E and 28W (averaged) and cotton Field 29.

ature and soil heat flux density were observed. Soil heat flux at the surface with 75% vegetative cover was calculated by using a weighting scheme of the three soil heat flux values calculated by eqs. 2 and 4

$$\overline{GS}=0.125GS_b+0.375GS_v+0.50GS_p \tag{5}$$

Values of GS_b, GS_v and GS_p represent the surface soil heat flux in the thatch cover, under the vegetation, and in partial cover, respectively.

Shading caused by the furrow profile (Table 1) in the cotton fields significantly influenced soil heat flux and soil temperatures. Mean soil heat flux density ($\overline{GS}$) was calculated by weighting the flux values from each heat flow plate by the horizontal area it represented (Fig. 1). These weighting factors produced the following equation for $\overline{GS}$

$$\overline{GS}=0.10(GS_{wb}+GS_{eb})+0.375(GS_{ws}+GS_{es})+0.05(GS_b) \tag{6}$$

where the first letter of the subscripts signifies whether the sensor is on the west (w) or east (e) facing side of the furrow or at the bottom (b) of the furrow (see Fig. 1). The second letter of the subscript pertains to the position of the sensor either on the bed (b) or side (s) of the furrow. The weighting factors were estimated by the topographic measurements of the furrows listed in Table 1. The value for the bed (0.1) came from values of zero depth indicated for the 0, 0.1 and 0.9, 1.0 m measurements. The fraction for the sides came from considering the furrow's vertical and horizontal dimensions on a 1:1 scale. This gave the sides of furrows taking up nearly 0.75 m of the 1-m row spacing, and left 0.05 m for the furrow bottom. The east site had slightly larger values of Rn and $\overline{GS}$ around midday. These differences, however, are probably negligible compared to measurement errors due to sensor placement and accuracy in the instruments. Error in the estimate of $\overline{GS}$ due to inaccurate estimates of the weighting factors for the sides and bottom of the furrow was considered. The side soil heat flux values were also given a weighting factor of 0.70 while the furrow bottom soil heat flux was multiplied by 0.10. The effect on the magnitude of $\overline{GS}$ was negligible.

Field 29 provided a unique opportunity for studying the behavior of $\overline{GS}$ and Rn before and after irrigation. There was a marked change in net radiation and surface soil heat flux caused by the flood irrigation. The night-time spike in $\overline{GS}$ shown in Fig. 2(b) reveals the approximate time when the site was flooded. Moreover, during the morning hours of DOY 164 the relatively low values of $\overline{GS}$ are caused by standing water in the furrows. By the afternoon the water had infiltrated into the soil but the soil surface was still very wet.

It is uncertain whether the depth of the probes may have changed as a result of soil movement during irrigation and subsequent infiltration. However, Fig. 2(b) shows that after the water had infiltrated into the soil, the temporal trend in $\overline{GS}$ is similar to the pattern observed before irrigation (i.e. DOY 163).

Values of $\overline{GS}/Rn$

Figure 2 illustrates the relative magnitudes of $\overline{GS}$ and Rn observed for the different fields. This figure suggests larger differences in Rn exist than in $\overline{GS}$ among the sites.

Figure 3 illustrates the ratio $\overline{GS}/Rn$ for bare soil and alfalfa during most of the daylight hours. Data available for a portion of the day on DOY 162 are also plotted. For bare soil Field 32, the maximum value $\overline{GS}/Rn \simeq 0.4$ occurs between 0800 and 0900 h MST and it gradually decreases to about 0.29 (± 0.05) around midday (i.e. 1030–1430 h MST). This decrease over time is the result of the time lag in surface temperature. For alfalfa, the values of $\overline{GS}/Rn$ were smaller than the bare soil (Fig. 3). There appears to be a slight trend of decreasing $\overline{GS}/Rn$ from DOY 162 to DOY 165, which is consistent with the rapid growth of alfalfa after irrigation. The average midday value of $\overline{GS}/Rn$ was $\simeq 0.16$ (± 0.035).

The three cotton fields had the same general shape in $\overline{GS}/Rn$ versus time (Fig. 4). The midday $\overline{GS}/Rn$ for Cotton 28E was $\sim 0.27 \pm 0.02$ compared to $\sim 0.24 \pm 0.03$ for Cotton 28W. The larger $\overline{GS}/Rn$ for the east site seems to contradict the concept of decreasing $\overline{GS}/Rn$ with increasing amount of vege-

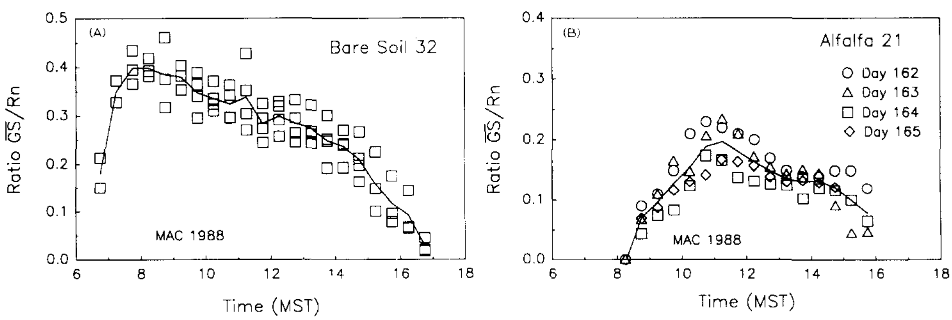

Fig. 3. Daytime values of $\overline{GS}/Rn$ for DOY 162-165 in (a) Field 32 bare soil and (b) Field 21 alfalfa. For the alfalfa field, each day is represented by a symbol.

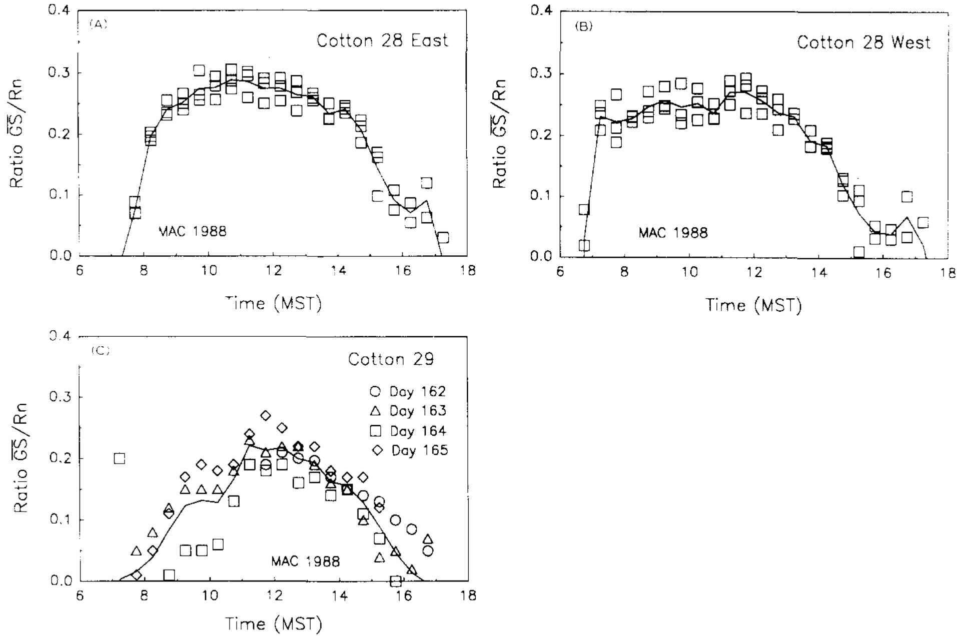

Fig. 4. Daytime values of $\overline{GS}/Rn$ for DOY 163-165 in (a) Cotton 28 east site, (b) Cotton 28 west site, and (c) Cotton 29.

tation. Also, in the early morning, Figs. 4A and 4B suggest a time lag of about 1 h before $\overline{GS}/Rn$ becomes greater than zero in 28E compared to 28W. This occurrence may be related to the amount of shading caused by differences in average vegetation heights, which becomes accentuated for high solar zenith angles. Still, these differences seem trivial when one considers the standard deviations of $\overline{GS}/Rn$. Furthermore, it is likely that errors in sensor placement and instrument calibrations are of the same order of magnitude as the differences in $\overline{GS}/Rn$ for the two sites illustrated in Fig. 4.

Water standing in the furrows of Cotton 29 on the morning of DOY 164 had significantly reduced $\overline{GS}/Rn$ compared to DOY 163 (Fig. 4C). By midday the differences in $\overline{GS}/Rn$ due to irrigation were relatively small even when corrected for soil diffusivity effects. Thus the effect of soil moisture on values of $\overline{GS}/Rn$ for Field 29 appear small and may be negligible (Clothier et al., 1986). This result, however, may not be generally applicable (e.g. Rijks, 1968). Midday values of $\overline{GS}/Rn$ were approximately 20% lower for Cotton 29 than for Cotton 28. This result is reasonable since the cotton in Field 29 was larger and covered more of the soil than the cotton in Field 28.

Remotely sensed estimates of $\overline{GS}$/Rn

Values of the simple ratio, NIR/Red, normalized difference vegetation index, NDVI, and the corresponding midday values of $\overline{GS}/Rn$ are listed in Table

4. The relationships between the vegetation indices and $\overline{GS}/Rn$ are illustrated in Fig. 5. A linear relationship between the two variables appears to be adequate. A comparison of the regression results (see Table 6) suggests NDVI is more highly correlated with $\overline{GS}/Rn$ than NIR/Red. This finding is supported by the relationships developed between leaf area index and $\overline{GS}/Rn$ (Choudhury et al., 1987), and leaf area index and NDVI (e.g. Asrar et al., 1984). Similar regression equations were computed with the corrected $\overline{GS}$ values. Comparison of the regression equations using corrected and uncorrected values of $\overline{GS}$ (see Table 6) revealed that the corrected values produced a lower correlation with the vegetation indices, but maintained slopes and intercepts which were statistically no different than the uncorrected. This provides some confidence in the relationships illustrated in Fig. 5.

Although there are only 11 data points, the least squares regression equation for NIR/Red has a slope and intercept comparable to the expression of Cloth-

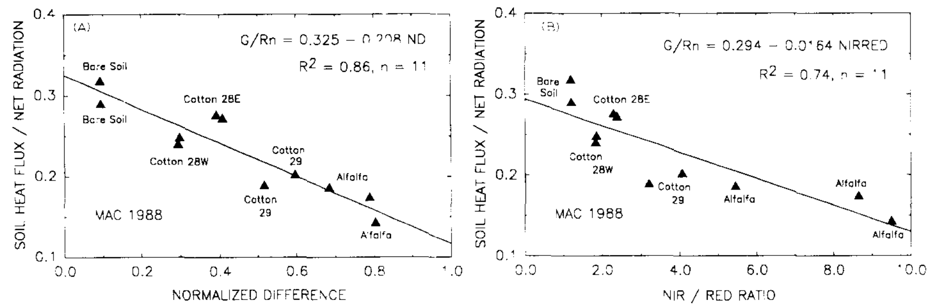

Fig. 5. Comparison of GS/Rn averaged around midday (i.e. from 1030 to 1430 h MST) for each field versus the NIR/Red vegetation index (a) and the NDVI (b). The lines are linear least squares fit to the data. The equation and coefficient of determination, R^2, are given.

TABLE 6

Least squares regression results between the vegetation indices and $\overline{GS}/Rn$ for both corrected and uncorrected values of $\overline{GS}$

Vegetation index	Coefficient of determination R^2	Slope (SE)	Intercept	SE of $\overline{GS}/Rn$ estimate
Uncorrected				
NIR/Red	0.74	-0.016 (± 0.003)	0.29	0.03
NDVI	0.86	-0.21 (± 0.03)	0.32	0.02
Corrected				
NIR/Red	0.67	-0.017 (± 0.004)	0.32	0.04
NDVI	0.66	-0.20 (± 0.05)	0.35	0.04

ier et al. (1986), which was produced using 74 values. The slope in the Clothier et al. (1986) equation is about 20% less (i.e. 0.0133) than the one in Table 6. This difference may be real because the Clothier et al. (1986) results pertain only to alfalfa while the present analysis contains data from different types of vegetation (i.e. cotton and alfalfa) and soil surface conditions (i.e. furrowed and flat surfaces). However, more data are required over different crops and surface conditions to ascertain the generality of the expressions shown in Fig. 5. For example, in the full canopy cover limit where NDVI approaches 0.9 the equation in Fig. 5(b) yields $\overline{GS}/Rn \simeq 0.14$, which is higher than the normally quoted range of 0.5–0.1. On the other hand, taking NIR/Red $\simeq$ 14 for full cover alfalfa (Clothier et al., 1986) gives, with the equation in Fig. 5(a), $\overline{GS}/Rn \simeq$ 0.06.

In Table 4, spectral data collected close to midday on DOY 162 for the cotton fields did not have actual measurements of midday $\overline{GS}/Rn$. Note that the estimates of NIR/Red and NDVI are between 60 and 80% of the values collected earlier in time on DOY 163. This reduction in the vegetation indices due to soil shading is expected (e.g. Jackson et al., 1979). The values of $\overline{GS}/Rn$ estimated with the expression for NIR/Red in Table 6 are given in Table 4. The difference between $\overline{GS}/Rn$ estimated for DOY 162 and $\overline{GS}/Rn$ measured for DOY 163 is relatively small (i.e. roughly 10% on average). The same result was obtained using the NDVI equation. This lack of sensitivity is a consequence of the relatively small slope of the least squares regression equations shown in Fig. 5. Hence, it may be possible to estimate midday $\overline{GS}/Rn$ with acceptable error from spectral data collected at considerably different solar zenith and azimuth angles, as long as there is not significant soil shading.

CONCLUSIONS

In summary, the major impetus for this field experiment was to extend the method given by Clothier et al. (1986) of estimating the surface soil heat flux from multispectral data to different types of vegetated surfaces and cover. The results presented in Fig. 5 are encouraging because it appears that spectral data collected from aircraft and satellite altitudes may provide a means of computing the relative magnitude of $\overline{GS}$ from estimates of Rn for different types of vegetation, cover, and soil topography. In this experiment the range in $\overline{GS}/Rn$ observed was about 0.15 with a standard error of around 0.03 (Table 6); thus, the midday available energy ($Rn - \overline{GS}$) ranges from approximately 0.70 Rn to 0.85 Rn (± 0.03). If one assumes that Rn is measured accurately (see Addendum) the error in available energy would be roughly 4% (i.e. 0.03/ 0.70 or 0.03/ 0.85). If this technique can be generalized for use over many different vegetated surfaces, including furrowed row crops, this would result in more accurate estimates of the surface energy balance over agricultural areas with length scales from meters to kilometers than is possible with surface meteorological measurements alone.

Future analyses will involve comparing estimates of $\overline{GS}/Rn$ obtained from aircraft and satellite sensors with ground-based point measurements of $\overline{GS}/Rn$. In addition, a more theoretical analysis of the effects of sun angle and soil reflectance on the relationship between vegetation indices and the midday value of $\overline{GS}/Rn$ will be considered. This will be a crucial step for regional energy balance studies.

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ADDENDUM

Some preliminary investigations into the performance of shielded net radiometers used in this study, which require no pressurization (NP) for their domes compared with pressurized types, suggest differences in the daytime period are of the order of 10%. There is a general consensus that the NP ra-

TABLE 1a

Least squares regression results between the vegetation indices and $\overline{GS}/Rn$ for both corrected and uncorrected values of $\overline{GS}$ and a 10% reduction in Rn-values

Vegetation index	Coefficient of determination R^2	Slope (SE)	Intercept	SE of $\overline{GS}/Rn$ estimate
Uncorrected				
NIR/Red	0.74	−0.0018 (±0.004)	0.33	0.03
NDVI	0.86	−0.23 (±0.03)	0.36	0.02
Corrected				
NIR/Red	0.67	−0.019 (±0.004)	0.36	0.04
NDVI	0.66	−0.22 (±0.05)	0.39	0.04

diometers overestimate *Rn*; however, the magnitude of the error will vary with meteorological and surface conditions, and the type of radiometer used (Nie et al., 1989). To assess the impact that overestimates of *Rn* may have on the results, changes in the regression coefficients in Table 6 to a 10% reduction in the *Rn* values at all sites are presented in Table 1a. It can be concluded that differences in the regression coefficients in Tables 6 and 1a are relatively small.

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